# NASA GRANT NAG5-6466:
# INVESTIGATION STATUS REPORT (May 2000)

PROJECT TITLE:

**Optical and Ancillary Measurements at High Latitudes in Support of the MODIS Ocean Validation Program**

PRINCIPAL INVESTIGATORS:

**Dariusz Stramski**
Marine Physical Laboratory, Scripps Institution of Oceanography
La Jolla, CA 92093-0238
Tel: ( 858) 534 3353
Fax: (858) 553 7641
e-mail: stramski@mpl.ucsd.edu

**Malgorzata Stramska**
Hancock Institute for Marine Sciences, University of Southern California
Los Angeles, CA 90089-0371
Tel: (213) 740 5813
Fax: (213) 740 8123
e-mail: stramska@usc.edu

## I. Primary objectives of the project

The overall goal of the project is to validate MODIS ocean color algorithms at high latitudes in the Arctic Seas. The specific objectives include:
(1) To identify and quantify errors in MODIS-derived Level-2 data of the spectral water-leaving radiances and chlorophyll concentration in the Greenland and Norwegian Seas.
(2) To develop understanding of the errors.
(3) To improve in-water ocean color algorithms for the retrieval of chlorophyll concentration in the investigated region.

## II. Summary of tasks for the reporting period June 1, 1999 - May 31, 2000

We pursued five major tasks:
(1) Carry out optical and ancillary measurements during the Arctic cruise in June-August 1999.
(2) Process the collected data and carry out analysis to examine ocean color algorithms including the quantification of errors in the Level-2 satellite ocean color data products and the development of improved regional algorithm for retrieving chlorophyll concentration.
(3) Using radiative transfer simulations develop models for the retrieval of the ocean inherent optical properties (IOPs) from the apparent optical properties (AOPs) and for the analysis of the effects of bubble entrainment by breaking wind waves on remote-sensing reflectance.
(4) Prepare the field experiment in summer 2000.
(5) Write publications.

### Task 1. Measurements during the 1999 cruise

We completed our second field campaign in the Arctic on research vessel "Oceania" operated by the Polish Academy of Sciences. The study area extended from 60$^{o}$ to 80$^{o}$N within the meridional zone between 3$^{o}$ and 20$^{o}$E, and included Norwegian Sea, Greenland Sea, and Spitsbergen Bank. Measurements were made during three legs of the cruise:
- Leg 1: Tromso (Norway) – Longyearbyen (Spitsbergen) June 22 - July 9, 1998;
- Leg 2: Kongsfjorden (Spitsbergen), July 11 - July 22, 1998;
- Leg 3: West Spitsbergen Current - Greenland Sea, July 24 – August 5, 1998.

In situ optical measurements were made down to a depth of 100 – 200 m in close proximity to water samples collected from discrete depths. We used two sensor packages:
(i) SeaWiFS Profiling Multichannel Radiometer (SPMR, Satlantic) for measuring downwelling irradiance and upwelling radiance within 13 spectral wavebands in free fall mode away from ship perturbations. The instrument is equipped with a set of filters matching the SeaWiFS/MODIS bands as well as several wavelengths which are not included in the current satellite ocean color sensors (for example, in the UV range).
(ii) Multisensor Datalogger System (MDS) for measuring vertical profiles of physical properties and inherent optical properties of seawater. The system includes SeaBird Sealogger 25 (SB25) with temperature, conductivity, and pressure sensors, two single wavelength (488 and 660 nm) beam transmissometers (WetLabs), chlorophyll fluorometer (WetLabs), and PAR sensor (Biospherical). Hydroscat-6 sensor (HobiLabs) for measuring measurements of light backscattering at six wavelengths and two a-βeta instruments (HobiLabs) for measuring the total absorption coefficient, each at a single wavelength, were also integrated with this system. We also measured the spectral water-leaving radiance from above the sea surface and atmospheric aerosol optical thickness at 443, 560, 670, and 865 nm using the SIMBAD instrument, which was made available by Dr. Robert Frouin from Scripps Institution of Oceanography.

Water samples from discrete depths were used to measure particulate absorption from 380 to 750 nm by means of filter pad technique with a bench-top double-beam spectrophotometer equipped with an integrating sphere. The measurements on filters were made in both the transmittance and the reflectance mode. We also conducted unique absorption experiments with the purpose of determining the pathlength amplification factor for natural particle assemblages collected on the filters, which is essential for accurate determination of particulate absorption. Samples for the analysis of chlorophyll-*a* with three techniques (HPLC, spectrophotometry, fluorimetry) and particulate organic carbon POC (dry combustion technique) were also collected. The analyses of water samples were carried out in collaboration with the bio-optical team from the Polish Academy of Sciences.

In addition, a number of observations were made as part of the Polish program including deep profiles of water temperature and conductivity, ocean currents, meteorological parameters, marine aerosol, sky conditions, and sea state. Digitial pictures of sea surface were taken for the analysis of whitecap coverage.

**Task 2. Data processing and analysis**

Data processing including data quality control and conversion to physical units has been completed. We also completed calculations of various optical quantities which are relevant to ocean color algorithms such as remote-sensing reflectance, spectral attenuation coefficient for downwelling irradiance and upwelling radiance, and spectral water-leaving radiance. These data cover a broad range of optical water types from clear ocean waters to turbid waters of the Spitsbergen Bank, as well as variable weather conditions from calm seas to stormy weather.

We compared the normalized water-leaving radiances ($L_{wn}$) and chlorophyll-*a* concentrations (Chl) estimated from our ship-based measurements and high resolution (HRTP) SeaWiFS data. Following the criteria described by McClain et al. (1998) we excluded from this comparison the SeaWiFS data with land, cloud/ice, sun glint and atmospheric correction failure, as well as data with negative $L_{wn}$ in any of the five blue-green wavebands. We used radiometric and chlorophyll data collected within 2 hours and 3 hours from the local solar noon, respectively. Time difference between SeaWiFS and *in situ* observations was less than 2 hours and 4 hours for radiometric and chlorophyll comparisons, respectively. The results of this comparison, which include data from the cruises in 1998 and 1999 are presented in Table 1 below.

Table 1. Statistics of the *in situ* and SeaWiFS match-up data for the Norwegian and Greenland Seas.

| Parameter | Mean ratio SeaWiFS / in situ | Number of observations |
|---|---|---|
| $L_{wn}$ (412) | 0.54 | 13 |
| $L_{wn}$ (443) | 0.74 | 13 |
| $L_{wn}$ (490) | 0.91 | 13 |
| $L_{wn}$ (510) | 0.90 | 13 |
| $L_{wn}$ (555) | 0.86 | 13 |
| $L_{wn}$ (490)/$L_{wn}$ (555) | 1.06 | 13 |
| Chl | 2.30 | 20 |
| in situ Chl < 0.5 mg $m^{-3}$ | 3.28 | 12 |
| in situ Chl > 0.5 mg $m^{-3}$ | 0.81 | 8 |

The results presented above indicate that while some quantities show relatively good agreement, others show significant deviations between *in situ* and satellite-derived values. In particular, we observed large deviations for water-leaving radiances in the blue spectral region. The $L_{wn}(490)/L_{wn}(555)$ ratio shows, however, a fairly good agreement between *in situ* and satellite-derived values. Therefore, we expect that the observed errors in the SeaWiFS-derived chlorophyll, which are greatest at low Chl, can be primarily attributed to performance of the NASA standard chlorophyll algorithm referred to as OC2 (O'Reilly et al., 1998).

Figure 1 compares the NASA OC2 algorithm with our data on the chlorophyll concentration Chl versus the blue-to-green reflectance ratio $R_{rs}(490)/R_{rs}(555)$. Our data show significant scatter about the OC2 curve and suggest systematic overestimation of Chl by OC2 algorithm at low chlorophyll concentrations. Resolving the question whether the patterns for the Greenland Sea and Norwegian Sea are significantly different will require more data, especially low chlorophyll data in the Norwegian Sea. Our present analysis is focused on developing the understanding of the seemingly random variations in the data points in Figure 1 and possible systematic departures from the OC2 algorithm. This understanding will be critical to making improvements in Chl retrieval from satellite-derived reflectance.

To a first approximation, the variability in $R_{rs}(490)/R_{rs}(555)$ is driven by a product of the spectral ratios of the backscattering and absorption coefficients, $[b_b(490)/b_b(555)]$ $[a(555)/a(490)]$. Our data showed that the overall range of values for the $b_b$ ratio is quite small, and that this ratio did not change significantly with Chl in the Norwegian and Greenland Seas (Figure 2a). Therefore, the observed variability in the reflectance ratio is expected to be strongly dependent on the variability in the absorption ratio $a(555)/a(490)$. Accurate in situ measurements of the total absorption coefficient $a(\lambda)$ are very difficult and we did not have such a capability during our field experiments. However, we obtained reasonable estimates of $a(\lambda)$ from the model based on radiative transfer simulations (Stramska et al., 2000) using our in-water measurements of the backscattering coefficient and reflectance. We found that the sum of absorption by pure seawater and particles dominated the total absorption in the blue-green spectral region while the dissolved organic materials had relatively small contribution. Phytoplankton contributed, on average, 80 and 70% to total particulate absorption $a_p$ at 490 and 555 nm, respectively. The total particulate absorption and phytoplankton absorption were highly correlated in the blue ($r^2 = 0.95$ and 0.92 at 442 and 490 nm respectively) but the correlation was lower at 555 nm ($r^2 = 0.69$). In addition, we found that our estimates of Chl-specific particulate absorption in the blue are systematically higher than the values obtained in various oceanic regions at lower latitudes (Bricaud et al., 1998). This trend was not, however, observed for 555 nm.

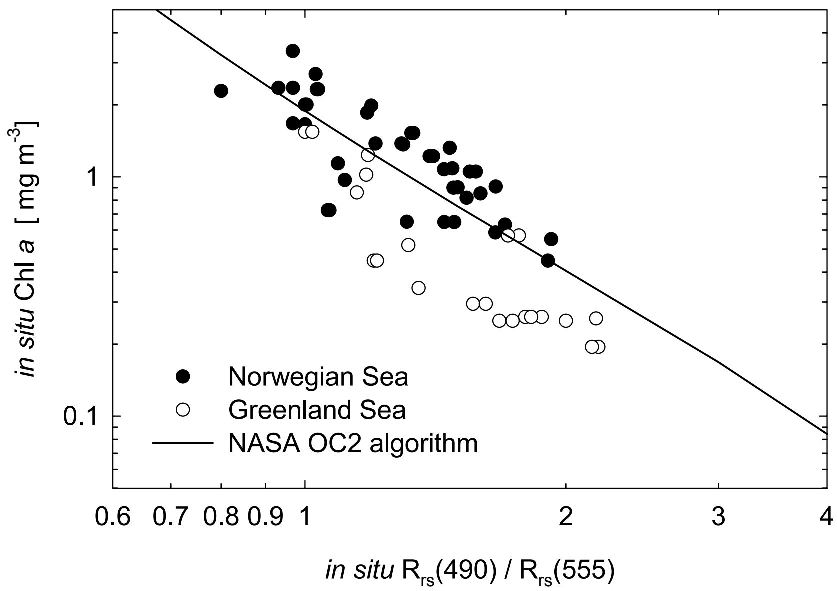


Figure 1. The chlorophyll concentration plotted versus the spectral ratio of remote-sensing reflectance as measured in the Norwegian and Greenland Seas. The NASA OC2 algorithm is also shown.

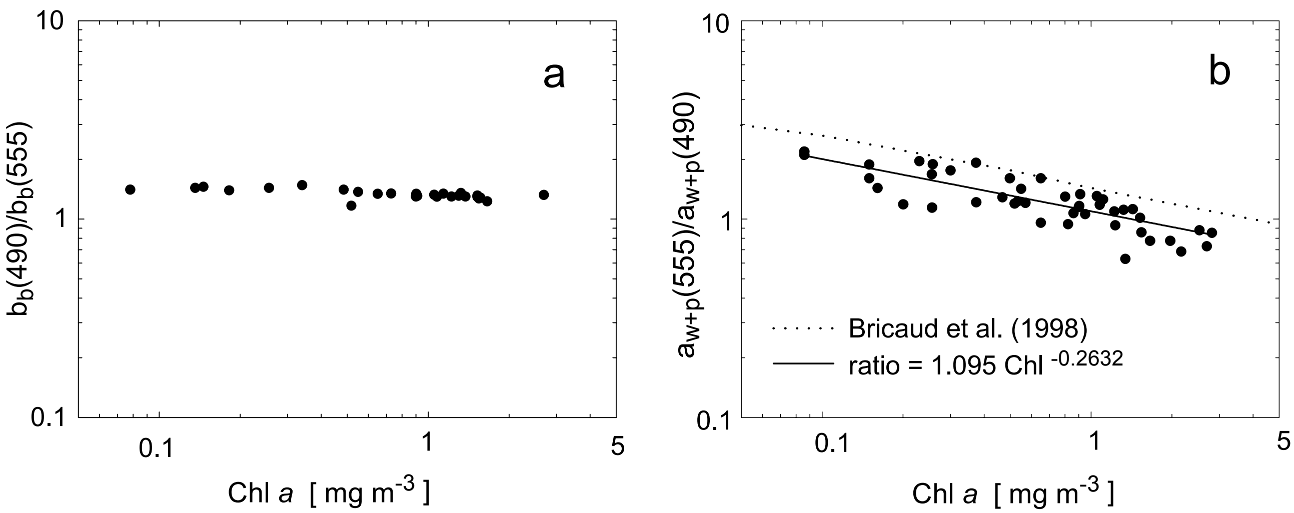


Figure 2. The spectral ratio of backscattering coefficient (panel a) and the absorption coefficient due to water and particles (panel b) plotted verus chlorophyll concentration. The data points represent our observations in the Norwegian and Greenland Seas and the dotted line in panel b represents the data set from lower latitudes described in Bricaud et al. (1998).

Figure 2b shows the spectral (555/490 nm) ratio of the sum of absorption by pure water and particles ($a_{w+p}$) as a function of Chl. The solid line is the best-fit regression for our data points and the dotted line represents the best-fit to the large data set from low latitudes described in Bricaud et al. (1998). Note that nearly all our data points are located below the regression of Bricaud et al. (1998). This suggests that for any value of Chl the Greenland and Norwegian Seas could exhibit a tendency to lower values of the blue-to-green spectral ratio of $R_{rs}$ compared to low-latitude data sets such as that used to develop the OC2 algorithm (provided that the backscattering properties do not show significant differentiation between the high- and low-latitude systems which still remains an open question). This tendency is seen for the subset of our data collected at low chlorophyll concentration in the Greenland Sea where the OC2 algorithm seems to show a systematic bias. Because the variability in the absorption coefficient observed at any Chl can be an important source of error in the retrieval of pigment concentration from ocean color observations, much of our present analysis is focused on this variability. The detailed analysis of our validation results, bio-optical relationships, and chlorophyll algorithm in the Norwegian and Greenland Seas is the subject of the manuscript that is being prepared for publication (Stramska et al., in preparation).

**Task 3. Modeling efforts**

We completed three major modeling tasks. The first model that we developed based on numerical simulations of radiative transfer provides a set of equations for estimating the absorption, $a$, and backscattering, $b_b$, coefficients in the blue-green spectral region from in-water measurements of downwelling irradiance, $E_d$, upwelling irradiance, $E_u$, and upwelling nadir radiance, $L_u$ (Stramska et al., 2000). The model does not require any assumptions or *a priori* knowledge about the spectral behavior of the inherent optical properties (IOPs), the angular distribution of incoming solar radiation, sky conditions, and sea surface state. The model provides a tool for estimating missing IOP data and for quality control of simultaneous measurements of IOPs (such as absorption and backscattering coefficients) and apparent optical properties (AOPs; such as reflectance and diffuse attenuation of irradiance). This capability is important because the present instruments used in the determinations of $a(\lambda)$ and $b_b(\lambda)$ do not provide direct measurements of these coefficients, and significant uncertainties may be involved in these determination. On our cruises we measured the absorption coefficient by particles but the total absorption coefficient was determined from this model.

The second model was also developed by means of radiative transfer simulations to estimate the absorption, total scattering, and backscattering coefficients in the upper ocean from irradiance reflectance just beneath the sea surface, $R(0^-)$, and the average attenuation coefficient for downwelling irradiance, $<K_d>_1$, between the surface and the first attenuation depth (Loisel and Stramski, 2000). The sun position is required as input but no assumptions about IOPs are involved. The model has potential to be useful in satellite ocean color applications because the model inputs, $R(0^-)$ and $<K_d>_1$, can be retrieved from remotely-sensed water-leaving radiances, and the model outputs, $a$ and $b_b$, are the major determinants of remote-sensing reflectance. The capability to retrieve the inherent optical properties, $a$ and $b_b$, of the ocean from satellites would be a significant advancement. We plan on applying this model to examine this capability.

Finally, in order to examine the effects of intermittent nature of bubble entrainment on remote-sensing reflectance we completed a series of radiative transfer simulations, in which the scattering properties of the upper ocean were defined to represent the effect of realistic temporal and depth variations in bubble concentration (Stramski and Tegowski, submitted). The input to the radiative transfer model describing light scattering by bubbles was driven by our acoustic measurements of bubble concentrations made during the Arctic cruise in 1998. This study showed that the remote-sensing reflectance can increase significantly (> 2-fold) due to bubble entrainment and these large variations occur over time periods on the order of minutes or less. The bubble clouds have a spectral effect on ocean reflectance such that the water patch containing bubbles will appear greener or more yellowish than the surrounding waters with no bubbles. Thus the spectral ratios of reflectance used in ocean color algorithms (such as 490-to-555 nm ratio) will be affected by bubble clouds. These results have also implications for ground-truth determinations of remote-sensing reflectance both from above–water and underwater measurements.

**Task 4. Preparation of the field experiment**

Details of our involvement in the 2000 cruise were discussed with the Institute of Oceanology, Polish Academy of Sciences. Part of the discussion took place at Stramski's lab at Scripps Institution of Oceanography in April 2000 during the visit of two Polish scientists, Jan Piechura, the Chief Scientist on the cruise, and Slawomir Kaczmarek, a member of the bio-optical team. According to the final plan we will participate in the first leg of the cruise (June 20- July 10) between Norway and Spitsbergen and in the second leg (July 12 – July 21) within the West Spitsbergen Current and Greenland Sea.

We have completed necessary repair, tests and calibrations of our equipment and it has been shipped to Poland for the cruise.

**Task 5. Publications**

Stramska, M., D. Stramski, B. G. Mitchell, and C. D. Mobley. 2000. Estimation of the absorption and backscattering coefficients from in-water radiometric measurements. *Limnol. Oceanogr*., 45, 628-641.

Loisel, H., and D. Stramski, 2000. Estimation of the inherent optical properties of natural waters from the irradiance attenuation coefficient and reflectance in the presence of Raman scattering, *Appl. Opt*. (in press, to be published in June 2000).

Stramski, D., and J. Tegowski. The effects of intermittent entrainment of air bubbles by breaking wind waves on ocean reflectance and in-water light field, *J. Geophys. Res*. (submitted).

Stramska, M., D. Stramski, R. Hapter, and S. Kaczmarek. Bio-optical relationships and algorithms for the analysis of ocean color in the Norwegian and Greenland Seas (in preparation for submission to *Int. J. Remote Sens*.).

## III. Plan of work for the next year

We will participate in the Arctic cruise on R/V *Oceania* from June 20 through July 21. After the field work, data will be processed and merged into one database that includes three cruises (1998, 1999, and 2000). Part of this database will be submitted to the NASA SeaBass data archive. The analysis of data will continue to address the objectives of our project. With the data collected in the summer 2000, we will be able to extend this analysis to a comparison of in situ measurements with MODIS-derived products. The extended data set will be also used to improve our analysis of bio-optical relationships and in-water ocean color algorithms for estimating chlorophyll concentration in the investigated region.

Our modeling efforts will focus on developing in-depth understanding of the origins of variability in ocean reflectance. In this effort we will combine our unique database of single-particle optical properties for various planktonic and non-living particles (Stramski et al., 1998) and radiative transfer simulations with a special version of Hydrolight code (Mobley, 1998).

Finally, our activities will include writing publications and presenting our results at conferences. The paper on bio-optical relationships and ocean color algorithms in the Greenland and Norwegian Seas will be presented at “Oceans from Space” symposium in Venice in October 2000.

## IV. References


Loisel, H., and D. Stramski, 2000. Estimation of the inherent optical properties of natural waters from the irradiance attenuation coefficient and reflectance in the presence of Raman scattering, *Appl. Opt*. (in press, to be published in June 2000).

McClain, C. R., M. L. Cleave, G. C. Feldman, W. W. Gregg, and S. B. Hooker. Science quality SeaWiFS data for global biosphere research. Sea Tech., September 1998, 10-16.

Mobley, C. D. 1998. *Hydrolight 4.0 User's Guide*, Sequoia Scientific, Inc., Mercer Island, Washington.

O'Reilly, J. E., S. Maritorena, B. G. Mitchell, D. A. Siegel, K. L. Carder, S. A. Garver, M. Kahru, and C. R. McClain. 1998. Ocean color chlorophyll algorithms for SeaWiFS. J. Geophys. Res., 103, 24937-24953.

Stramska, M., D. Stramski, R. Hapter, and S. Kaczmarek. Bio-optical relationships and algorithms for the analysis of ocean color in the Norwegian and Greenland Seas (in preparation for submission to *Int. J. Remote Sens*.).

Stramska, M., D. Stramski, B. G. Mitchell, and C. D. Mobley. 2000. Estimation of the absorption and backscattering coefficients from in-water radiometric measurements. *Limnol. Oceanogr*., 45, 628-641.

Stramski, D., A. Bricaud, and A. Morel. 1998. A database of single-particle optical properties. In: *Ocean Optics XIV Conference Papers*, Vol. 1., Kailua-Kona, Hawaii.

Stramski, D., and J. Tegowski. The effects of intermittent entrainment of air bubbles by breaking wind waves on ocean reflectance and in-water light field, *J. Geophys. Res*. (submitted).